The Frequency Transfer over 1000 km of Fiber Using the Optical Frequency Comb

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***Abstract*—We experimentally demonstrate a frequency transfer over 1000 km of fiber by exploiting the optical frequency comb. Through the feedback of the phase shifter, active phase noise cancellation is achieved. The fractional frequency instability of 2.4×10^{-15} at 1 s and 1.1×10^{-18} at 10000 s are measured respectively. The results support ultrastable frequency transfer applications via long-haul fiber links.**

***Index Terms*—frequency transfer, optical frequency comb, phase shifter, ultrastable, long-haul**

I. Introduction

The frequency transfer techniques offer a way for sharing high-precision frequency signals between remote parties [1], which is extremely important for the applications such as precision navigation [2], metrology [3], fundamental physics [4] and so forth. Fiber links can provide isolated transmission environment compared to the free space, so it has been proved that the fiber channel is more suitable for improving the stability of the frequency transfer [5].

To achieving long-haul microwave-frequency transfer tasks, two general techniques are considered to carrying the microwave-frequency signal. One is the radio-frequency modulation of the intensity of a laser, and the other is the optical frequency comb (OFC) [1]. The former can offer a good flexibility benefiting from the standard telecom components, while the later has advantage of its intrinsic high signal to noise ratio (SNR) [6]. For long-haul frequency transfer scenarios, in order to avoid the deterioration of the SNR caused by the limited modulation index of the modulated laser during the transmission, the OFC with stable repetition frequency is considered as a potential candidate for long-distance ultrastable applications.

In this work, we extend the microwave frequency transfer distance by propagation of an OFC to 1000 km using spooled fiber. An electrical phase shifter is employed as the feedback element to realize the compensation of the phase noise accumulated in the fiber link. The fractional frequency instability is 2.4×10^{-15}/s after active compensation, which improves the short-term instability by 2 orders of magnitude. The long-term instability with 1.1×10^{-18}/10000 s is also obtained.

II. Experiments

The structure of the frequency transfer system based on the OFC is shown in Fig. 1. The experimental setup is divided into four parts for simplicity, The source part (blue box), the link part (gray box), the measurement part (green box) and the noise compensation part (pink box).

In the source part, a homemade 15-nm-wide OFC centered at 1560 nm is employed, which has a repetition frequency of 100 MHz. The advantage of the OFC is that each two comb teeth has exact time interval, so that its repetition frequency is stable. In order to further stabilize the repetition frequency of the OFC, the repetition frequency is locked to a Cs microwave clock though the fiber loop optical-microwave phase detector technique [7]. In order to realize the phase detection before and after fiber transmission, a 50:50 beam splitter (BS) is used after the OFC to split the OFC signal into two parts. One of them is detected directly by a photodetector (PD), namely, PD_1, which is treated as the phase reference signal in the local site after passing a 100 MHz low pass filter in the measurement phase, and the other is exploited as the carrier of transmitting microwave frequency signal.

It should note that for reducing the influence of the dispersion of the OFC after the long-haul fiber transmission, a dense wavelength division multiplexer (DWDM) is employed to filter the spectrum of the OFC signal within the bandwidth of 0.8 nm with the central wavelength of 1551.72 nm, which refers to the channel-32 of the standard DWDM. Since the OFC used in this work is based on a figure-9 structure [8], the output

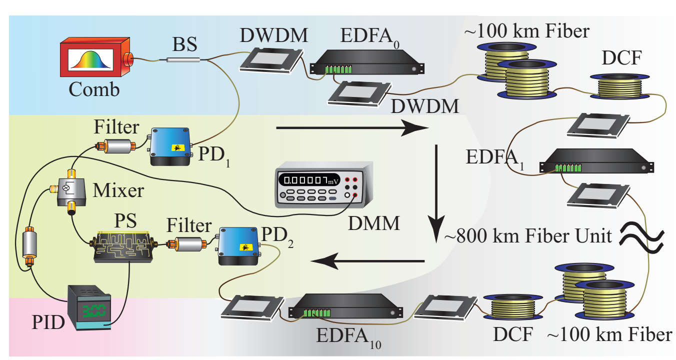

Fig. 1. Experimental setup of the frequency transfer using the OFC. BS: beam splitter; DWDM: dense wavelength division multiplexer; EDFA: erbium-doped fiber amplifier; DCF: dispersion compensation fiber; PD: photodetector; PS: phase shifter; DMM: digital multimeter.

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power is relatively low (∼1 mW). After passing the DWDM, only 20 μW of the signal remains. An erbium-doped fiber amplifier (EDFA), namely EDFA_0 is used to recover the power of the transmitted signal, and another DWDM is employed to eliminate out-of-band noise introduced by the EDFA. The lunched power is set to approximate 1 mW before entering the channel.

In the link part, ten 100 km-fiber-units with the identical structure are designed. For each unit, 100 km of spooled fiber with 24 dB of channel loss is built, followed by a dispersion compensation fiber (DCF) modular to compensate the dispersion during the 100 km of transmission. An EDFA is designed to compensate the 100 km of fiber loss in each unit. Since the total loss of the transmission link is beyond 240 dB, the gain of all EDFAs need careful calibration to adapt to the next stage transmission. Two DWDMs are inserted before and after the EDFA to filter the out-of-band noise introduced by the unpredictable fiber noise and the EDFA noise.

After passing through the 1000 km fiber link, the transmitted signal are measured by the PD_2 in the measurement step, then filtered by a low pass filter with 100 MHz bandwidth. The generated electrical signal is treated as a quasi sinusoidal signal carrying the repetition frequency information of the OFC, added additional phase noise introduced by the fiber link. The received signal in the remote site is therefore written by

$$V_{\text{remote}} = V \sin\left(2\pi \upsilon_0 t + \varphi_{\text{f}}\left(t\right)\right), \tag{1}$$

where $\upsilon_0 = 100\text{MHz}$ is the repetition rate of the OFC, and $\varphi_{\text{f}}\left(t\right)$ is the phase noise of the fiber link. We finally extract the phase noise information by mixing the local signal with the remote signal, which converts the phase variation to the voltage fluctuation of an electrical mixer, given by $V_{\text{out}}\left(t\right)$. The phase difference between the local and the remote sites is set to $\pi/2$ by adjusting the voltage of the phase shifter, and the fractional instantaneous frequency deviation from nominal can be then expressed as

$$y\left(t\right) := \frac{\dot{\varphi}_{\text{f}}\left(t\right)}{2\pi\upsilon_0}, \tag{2}$$

where $\varphi_{\text{f}}\left(t\right) = \arcsin\left[V_{\text{out}}\left(t\right)/V_0\right]$ is the phase deviation of the transmitted signal, and V_0 is the maximum output voltage of the mixer when adjusting the phase difference between input signals. A PID servo system is employed to compensate the phase noise of the system by adjusting the input voltage of the electrical phase shifter dynamically, so that the local and the remote microwave signals are synchronized precisely.

III. Experimental results

Based on the Experimental setup shown in Fig. 1, we finally achieve ultrastable long-haul frequency transfer via 1000 km of spooled fiber. The output voltage fluctuation is measured by a digital multimeter with $6^1/_2$ digits of resolution and the instantaneous frequency deviation is obtained by Eq. (2).

The comparison of the modified Allan deviation between before and after the phase compensation is shown in Fig. 2. It can be seen that the frequency instability of the scenario without compensation is measured to be 8.9×10^{-13}/ s. After phase compensation by the phase shifer, the improved modified Allan deviation of 2.4×10^{-15} at 1 s is obtained, which improves the short-term instability by 2 order of magnitude. Moreover, the long-term frequency instability is improved, which gets 1.1×10^{-18} at 10000 s.

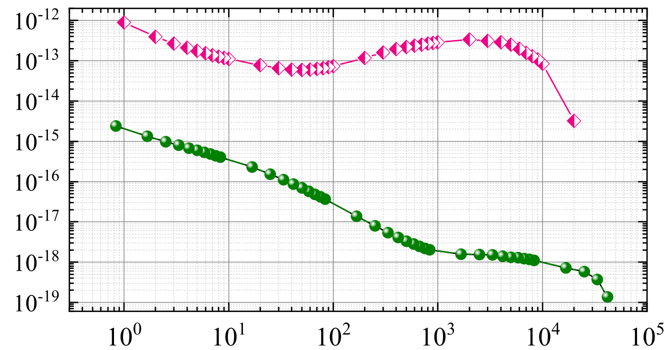

Fig. 2. The modified Allan deviation of the measurement results.

IV. Conclusion

In this work, we report a long-distance frequency transfer demonstration based on the OFC. Ultrastable microwave frequency transfer of the fundamental frequency of the pulse repetition rate is achieved via 1000 km of fiber, and the phase compensation method exploited by the phase shifter is realized to obtained the improved frequency instability of 2.4×10^{-15} at 1 s and 1.1×10^{-18} at 10000 s. The results support high precision long-distance frequency comparison between two microwave atomic clocks.

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